Prospects of experimentally reachable beyond Standard Model physics in inverse seesaw motivated non-SUSY SO(10) GUT

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The quest of a decent quantum field theoretic framework to describe the fundamental behavior of the newly discovered particles and their strange interactions, during the first half of the 20th century, was accomplished with the introduction of Standard Model (SM) of particle physics in 1967−68. Since then, the theory has been experimentally verified to the large accuracy in various collider experiments including the Large Hadron Collider (LHC) at CERN, latest in the list. All the particles predicted by the SM have not only been discovered but also fit perfectly in the model framework.

Despite the fact that SM has unraveled the gauge origin of fundamental forces and the structure of universe while successfully confronting numerous experimental tests, it has various limitations. For a nice summary on its excellencies and compulsions have a look at [1] and for extensive details on SM and beyond see [2]. Currently serious attempts are being made to probe: **(a)** Supersymmetry at LHC [3, 4], **(b)** Dark matter candidate in the galactic or extra galactic sources [5, 6, 7, 8, 9], **(c)** Lepton number and flavor violation in flavor violating processes [10, 11, 12], **(d)** Dirac or Majorana nature of neutrinos in neutrinoless double beta decay experiments [13, 14, 15, 16, 17, 18, 19, 20], **(e)** The hierarchy of light neutrino masses and CP violating phases at neutrino oscillation experiments [21, 22], **(f)** Proton lifetime at Super-K experiments [23], **(g)** The rare decay of mesons [24, 25], **(h)** Possible n-$\bar{n}$ oscillation [26], **(i)** Any exotic particle signature of beyond standard model physics at LHC [27, 28] and Tevatron, including larger gauge structure or seesaw signature.

The SUSY extensions of SM, with SUSY restoration at TeV energy scale, solves the gauge hierarchy problem and unifies the gauge couplings around $10^{16.25}$ GeV. The Minimal Supersymmetric Standard Model (MSSM) can be further extended to incorporate the tiny masses of neutrinos and their mixing through seesaw paradigm. In models with R-parity conservation, the lightest SUSY particle (LSP) is stable and weakly interacting massive particle (WIMP) which can be a possible candidate of cold dark matter [29] of universe. Hence, the SUSY grand unification theories (SUSY GUTs) as an extension of these models provide a very attractive framework for representing particles and forces [30]. An evidence of SUSY at the LHC would be a land-mark discovery which would certainly change the future course of physics. But, in the absence of any evidence of SUSY so far, it is worth while to explore new physics prospects of non-SUSY GUTs and, particularly, those based upon SO(10) which has grown in popularity as it unifies all fermions of one generation including the right-handed (RH) neutrino into a single spinorial representation. It provides spontaneous origins of P and CP violations. Most interestingly, in addition to predicting the right order of tiny neutrino masses, it can explain all fermion masses including large mixing angles in the neutrino sector. In fact neither seesaw mechanism, nor grand unification require SUSY per se. Although gauge couplings automatically unify in the MSSM, and they fail to unify in the minimal SM in one-step breaking of non-SUSY SU(5) or SO(10), they do unify once intermediate symmetries are included to populate the grand desert in non-SUSY SO(10). In addition, with intermediate gauge symmetries SO(10) also predicts signals of new physics which can be probed at low or accelerator energies.

We explore the prospects of TeV scale inverse seesaw mechanism [31], for generating the neutrino masses and mixings, in the non-SUSY SO(10) GUT framework [32]. This mechanism has the potential to be experimentally verified because of the low scale at which it can operate. Its implementation requires additional SO(10) singlet fermion per generation, which introduces a new mass scale μ_S in the theory. The TeV-scale seesaw requires $\mu_S \sim$ keV scale. In a theory with exact lepton number conservation (a global U(1) symmetry) $\mu_S = 0$, guaranteeing the masslessness of left-handed neutrinos. The breaking of non-SUSY SO(10) to left-right, $\mathrm{SU(2)_L \times SU(2)_R \times U(1)_{(BL)} \times SU(3)_C}\,[\equiv \mathrm{G}_{2213}](g_{2L} \neq g_{2R})$, symmetry is realized at GUT scale ($M_G \sim 10^{15.53}\,$GeV) by assigning vacuum expectation value (VEV) to the D-parity odd singlet in 45_H. The second step of breaking takes place by the right-handed (RH) triplet $(1, 3, 0, 1) \subset 45_H$ to $\mathrm{SU(2)_L \times U(1)_R \times U(1)_{(B-L)} \times SU(3)_C}$ ($\equiv G_{2113}$) gauge symmetry at intermediate scale ($M_R^+ \sim 10^{11}\,$GeV) whereas the third step of breaking to SM takes place by the G_{2213} sub-multiplet $(1, 1/2, -1/2, 1)$ of 16_H at TeV scale (M_R^0). Since, the actual parity restoration scale is high, $W_R^\pm$ gauge bosons are implausible at collider searches. The low mass ($\sim$ TeV) gauge boson (Z') and the associated non-unitarity effects of the TeV-scale inverse seesaw are the remnant of high scale left-right symmetry. The breaking scheme can be expressed as

$$\mathrm{SO(10)} \xrightarrow[45_H]{M_G} G_{2213} \xrightarrow[45_H]{M_R^+} G_{2113} \xrightarrow[16_H]{M_R^0} \mathrm{SM}, \tag{1}$$

and the Yukawa part of the Lagrangian is

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= Y^a 16.16.10^a_H + Y_\chi 16.1.16^\dagger_H + \mu_S 1.1 \\ &\ni Y_\nu \overline{l_L} N \phi_u + Y_\chi \overline{N} S \chi_R + \mu_S S^T S + h.c. \end{aligned} \tag{2}$$

which gives full inverse seesaw mass matrix with $M_D = Y_\nu v_u$, $M = Y_\chi v_\chi$ and μ_S as the elements of the matrix. The M_D matrix is determined using the available experimental data and SO(10) symmetry at GUT scale, through an iterative renormalization group evolution (RGE) process between M_R^0 and M_G. The matrix M is constrained using the non-unitarity constraints. Light neutrinos acquire masses from inverse seesaw formula $[m_\nu = (M_D M^{-1})\mu_S (M_D M^{-1})^T]$ and the heavy neutrinos get the quasi-Dirac mass

$M_H = \pm M + \mu_S/2$. Since μ_S doesn't play much role in any other prediction, we assume that it fits the neutrino oscillation data and determine it by inverting inverse seesaw formula and using experimental results of neutrino masses and mixings.

The model achieves precision gauge coupling unification, and predicts a low mass Z' making them suitable for implementation of TeV-scale inverse seesaw mechanism. The model can be testified through its predictions on observable non-unitarity effects and additional contributions to lepton flavor violating (LFV) decays for $\tau \to e\gamma$ (Br $\simeq 10^{-14}$), $\tau \to \mu\gamma$ (Br $\simeq 10^{-12}$), and $\mu \to e\gamma$ (Br $\simeq 10^{-16}$). We find that these contributions are as large as only $3-6$ order less than the current experimental bounds [33, 34] and are accessible to ongoing or future searches. The CP-violation in non-degenerate M scenario gives $\Delta J \simeq 10^{-4}$ due to non-unitarity effects. The quark-lepton symmetric origin of the Dirac neutrino mass matrix plays a crucial role in enhancing non-unitarity effects leading to enhanced LFV and leptonic CP-violation. Another testing ground for the model could be through the SO(10) prediction on gauge boson mediated proton decay for which dedicated search experiments are ongoing at Super-K. The model predicts proton lifetime $\tau_{pred}(p \to e^+\pi^0) = 2 \times 10^{34\pm0.32}$ yrs, which is very close to the current experimental bound $\tau_{exp}(p \to e^+\pi^0) > 1.4 \times 10^{34}$ yrs [23, 35].

For other possibilities of inverse seesaw motivated non-SUSY SO(10), we find that the minimal single-step breaking to the TeV scale gauge symmetry, SO(10) $\to G_{2113}$, is ruled out by gauge coupling unification constraints. The two-step breaking chains, SO(10) $\to G_{224D} \to G_{2113}$, SO(10) $\to G_{224} \to G_{2113}$, SO(10) $\to G_{214} \to G_{2113}$ and SO(10) $\to G_{2213D} \to G_{2113}$ with the minimal particle content are ruled out by the existing lower bound on proton lifetime. Here we denote $G_{214} \equiv SU(2)_L \times U(1)_R \times SU(4)_C$ and $G_{224} \equiv SU(2)_L \times SU(2)_R \times SU(4)_C$. The $G_{224D}(G_{2213D})$ is the D-parity preserving Pati-Salam (left-right) $[G_{224}(G_{2213})]$ symmetry.

A different class of TeV scale left-right (LR) gauge symmetry emerging from a non-SUSY SO(10) grand unification framework with minimal extension to accommodate experimentally testable extended inverse seesaw mechanism is possible in multi-step breaking of SO(10) to SM [36]. The breaking chain for this model is [37]

$$\mathrm{SO}(10) \xrightarrow[54_H]{M_G} G_{224D} \xrightarrow[210_H]{M_P} G_{224} \xrightarrow[210_H]{M_C} G_{2213} \xrightarrow[210_H]{M_R} G_{2113} \xrightarrow[126_H+16_H]{M_R^0} \mathrm{SM}, \quad (3)$$

and the corresponding Yukawa Lagrangian is

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= Y^a 16.16.10^a_H + f 16.16.\overline{126}^\dagger_H + y_\chi 16.1.16^\dagger_H + \mu_S 1.1 \\ &\ni Y_\nu \bar{l}_l N \phi_u + f N^C N \Delta_R + Y_\chi \overline{N} S \chi_R + \mu_S S^T S + h.c. \end{aligned} \quad (4)$$

which introduces another element $M_N = f v_{\Delta_R} (>> M)$ in the total neutrino mass matrix. The light neutrino masses are still governed by inverse seesaw formula but now the heavy neutrino masses split in to light ($M_S \sim M M_N^{-1} M^T$) and heavy sectors ($M_H \sim M_N$). The scalar particle mass assignment is ruled by *extended survival hypothesis*, therefore only those scalar particles get the mass of symmetry breaking scale which acquire the VEV and rest of the representations get GUT scale mass. The high scale ($M_P \sim 10^{14}$ GeV) parity restoration ensures the gauge coupling unification. The D-parity restoration pushes most of the larger sized sub-multiplets down to the parity restoring intermediate scale reducing the size of GUT-threshold effects on the unification scale and proton lifetime while the GUT-threshold effects on $\sin^2\theta_W$ or M_P have exactly vanishing contribution. The light neutrino masses are still governed by inverse seesaw formula. The masses of $W_R^{\pm}$ and Z_R gauge bosons, and RH neutrinos are $\mathcal{O}$(TeV) which are also directly accessible to accelerator tests. The model predicts **(1)** large CP and lepton flavor violation which is of same order as predicted in the previous model [32], **(2)** dominant contributions to neutrinoless double beta ($0\nu\beta\beta$) decay rate in $W_L^- - W_L^-$ channel through relatively light sterile neutrino exchanges, **(3)** experimentally reachable n-$\bar{n}$ oscillation time ($\tau_{n-\bar{n}} \sim 10^8 - 10^{11}$sec), **(4)** new bounds on Pati-Salam symmetry breaking scale ($M_C > 1.86 \times 10^6$ GeV) from gauge mediated rare kaon decay ($K_L \to \mu e$) etc. Although, proton lifetime is found to be beyond the accessible limit of ongoing experiments in the minimal scenario, introduction of a $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$ bi-triplet (3,3,1) between $10^7 - 10^{8.5}$ GeV brings down the unification to Hyper-K reachable scale [38].

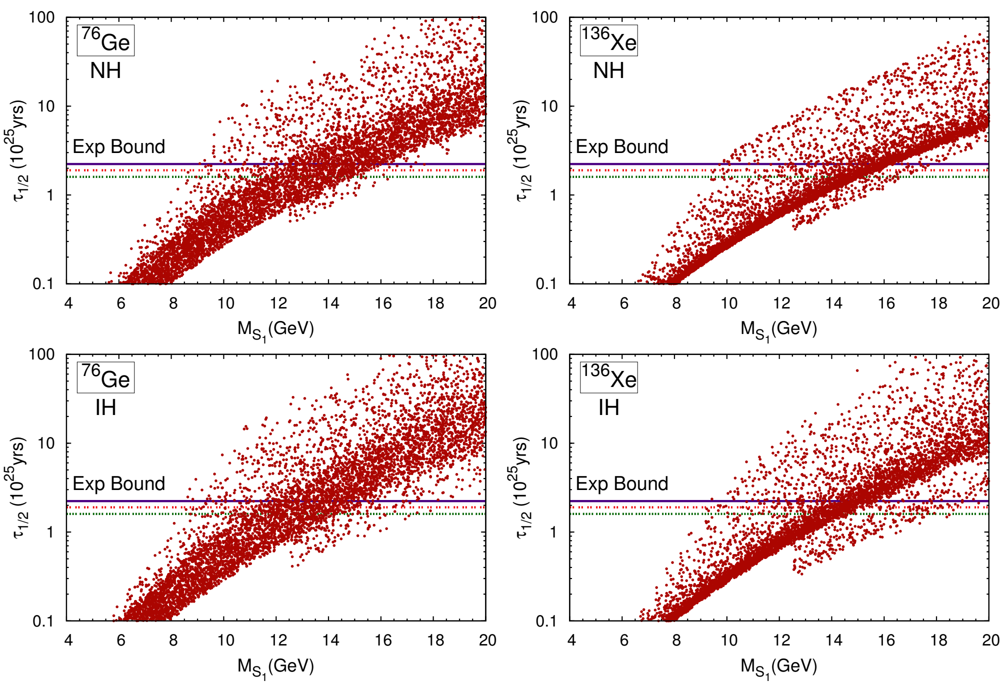

Figure 1: Comparative study of $0\nu\beta\beta$ contribution due to sterile neutrino, in two popular isotopes ^{76}Ge (left) and ^{136}Xe (right). First row: Normal hierarchy of light neutrinos. Second row: Inverted hierarchies of light neutrinos [39].

In addition to non-unitarity and LFV, the Dirac neutrino mass matrix is also found to play a crucial role in enhancing $0\nu\beta\beta$-decay rate. Lower bounds on $0\nu\beta\beta$-decay lifetime coming from Heidelberg-Moscow [13], KamLAND-Zen [15], GERDA [16], EXO-200 [17], and IGEX [19] experiments constrain any new contribution to $0\nu\beta\beta$-decay, severally. In the $W_L - W_L$ channeled sterile neutrino mediated $0\nu\beta\beta$-decay this constraint appears on the N-S mixing matrix M (Since other matrices M_D and M_N are fixed by the theory) which constrains physical mass of sterile neutrino, $\hat{M}_S$. In the Fig. we have plotted lifetime vs lightest sterile mass. Scatter plot gives the probability density of parameter space for the allowed values of two heavier sterile masses and arbitrariness in nuclear matrix elements for light and heavy neutrinos, Dirac and Majorana CP violating phases over the full allowed parameter space. We find that lightest sterile neutrino of $10 - 18\,\mathrm{GeV}$ mass is capable of explaining the possible future signature or claim of the Part of Heidelberg-Moscow experiment. Sterile neutrino mass $\hat{M}_{S_1} < 10\,\mathrm{GeV}$ is ruled out by the present bounds. In the quasi-degenerate light neutrino scenario the contribution though a signature of $0\nu\beta\beta$-decay can be explained by light neutrinos only. But, in a close competition among light and sterile contributions with relatively opposite phase may give very large lifetime, unreachable to current or future experiments. Also, $0\nu\beta\beta$-decay experiments in normal or inverted hierarchy wont be able to estimate the light neutrino mass. The CMBR study or Tritium decay experiments give the direct estimation of neutrino mass scale [40, 41].

Presence of G_{224D} at high scale plays a crucial role in lowering down the $W_R^{\pm}$ gauge boson masses without loosing the gauge coupling unification. Because of presence of G_{224} symmetry at energy scale as low as $10^{6.2}\,\mathrm{GeV}$, all the di-quarks Higgs scalars in $(3, 1, \bar{10})$ mediating n-$\bar{n}$ oscillation acquire the same scale mass predicting experimentally reachable n-$\bar{n}$ oscillation [20], without any serious fine tuning. This baryon number violating process may also be the possible source of baryonic asymmetry of universe therefore n-$\bar{n}$ oscillation search is equally crucial as proton decay search.

In case, only a TeV scale Z' is detected at LHC we explore the prospect of a GUT breaking scheme, with absence of $W_R^{\pm}$ gauge bosons between G_{224} and G_{2113}, is [37, 39]

$$\mathrm{SO}(10) \xrightarrow[54_H]{M_G} G_{224D} \xrightarrow[210_H]{M_P} G_{224} \xrightarrow[210_H]{M_R} G_{2113} \xrightarrow[126_H+16_H]{M_R^0} \mathrm{SM}. \tag{5}$$

The symmetry breaking scalar sub-multiplets in this scheme will also be different from the scheme of eq. ()[36]. Most of the observable predictions of [36] are still applicable in this model, except that $W_R^{\pm}$ boson masses are now beyond the currently accessible LHC limit. But, in sharp contrast to the model of eq. () [36] this model predicts Hyper-K verifiable $|\Delta(B-L)| = 0$ proton decay $\tau(p \to e^+\pi^0) \simeq 1.05 \times 10^{35 \pm 1.0 \pm 0.35}$ yrs.

Compare to SUSY SO(10) model with TeV scale LR symmetry [42], non-SUSY SO(10) models predict similar amount of LFV branching ratio. Large $0\nu\beta\beta$-decay contribution due to sterile neutrino exchange in W_L^--W_L^- channel, experimentally reachable n-$\bar{n}$ oscillation, rare kaon decay predictions are some of the important features of non-SUSY SO(10) models which are not easily achievable in SUSY models with TeV scale gauge boson prediction.

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